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14. ABSTRACT
This problem/phenomenon studied here, hurricane wake warming, can be viewed as a test case for warming the ocean surface generally. The key finding here is that the relevant heat flux is made up of two components: a slowly varying mean and the diurnally-varying heat flux, here represented by the noon maximum. The former determines the trend of surface temperature, and the latter determines the amplitude of the warming by setting the depth over which the mean heat flux is absorbed. The daily average heat flux alone is not sufficient to predict the depth over which the heat flux will be absorbed. This has direct implications for ocean modelling on synoptic and climate time scales.

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Impact of Typhoons on the Western Pacific: Temporal and horizontal variability of SST cooling Annual Report, 2012

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Long-term Goals/Scientific Background

This project is now at the end of the nominal grant period and at 18 months following the fall 2010 field phase of the ITOP program.

The long term goal of this research has been to understand how the spatial variation of ocean and hurricane parameters, e.g., upper ocean temperature gradient, initial mixed-layer depth, etc., contribute to hurricane-ocean interaction. With this understanding we should then be in position to make better forecasts of hurricane-ocean interaction, and especially of hurricane intensity (Emanuel et al., 2004).

Objectives

A specific question that came out of a study of satellite imagery from CBLAST hurricane Fabian was — What processes cause the cool SST in a hurricane wake to warm back toward pre-hurricane values? This SST warming (also called wake recovery) can be quite rapid. In the CBLAST Fabian case, the cool wake SST anomaly decayed (i.e., SST recovered back to pre-hurricane values) with an e-folding time of five days. In the CBLAST Francescase, the e-folding time was much longer, about two weeks.

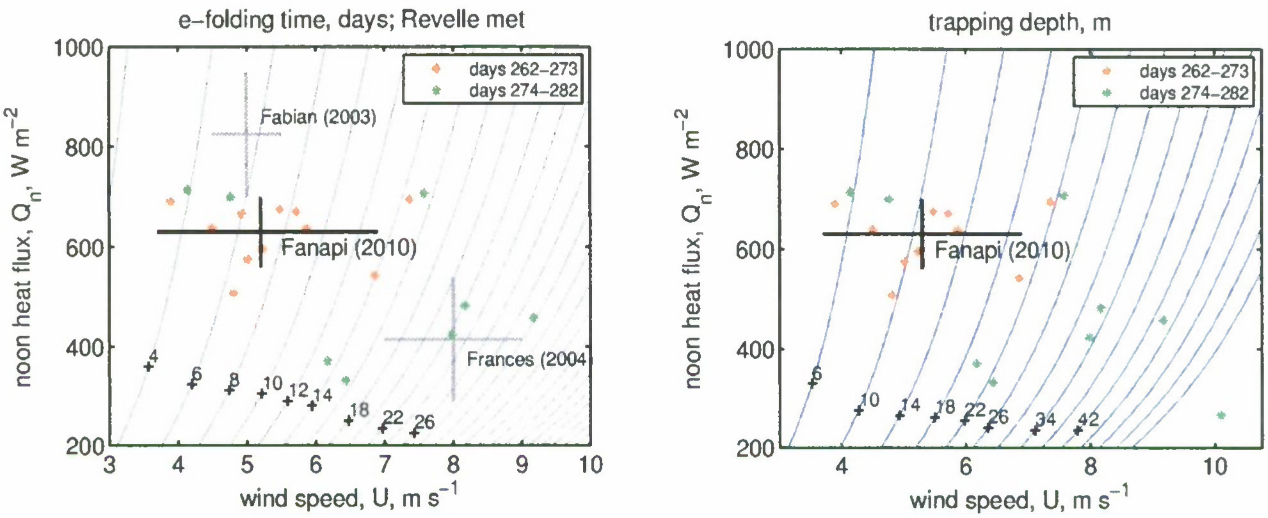

Figure 1: (left) The e-folding time (days) of a cool anomaly subject to the wind amplitude and noon maximum heat flux shown as the independent coordinates. The conditions appropriate for CBLAST hurricanes Fabian and Francesare shown, along with daily values (red and green dots) for the post-Fanapi period of ITOP. The e-folding time predicted by Eqn. (1) is shown as the background, contoured field, and is about 7 days for the period post-Fanapi. This is in good agreement with the observed e-folding time. (right) The trapping depth.

Approach

A model of this surface layer warming process was developed under a previous grant (Price et al., 2008) and can now be tested rigorously. This model is built around two hypotheses. The first, H1) that the SST warming is a local process driven in the main by an anomalous air-sea heat flux (anomalous compared to regions outside the cool wake). The heat flux over a cool wake is biased positive, typically by 40 - 80 W m^{-2}, simply because the SST in the wake is at first cooler than the surrounding regions (or summer conditions generally). This is a fairly direct inference from conventional air-sea heat flux parameterizations. The question then is – How can such a small heat flux produce the observed, rapid warming rate? The second hypothesis is that H2) the evident shallow trapping depth of this anomalous heat flux is determined not by the anomalous heat flux itself (which is much too small) but rather by the large amplitude diurnal cycle of the surface heat flux that (and this presumes that more or less fair weather conditions follow most hurricanes and typhoons).

These two hypotheses, combined with a heat budget, leads to leads to a simple solution for the e-folding time of the SST cool anomaly (Price et al., 2008),

$$\Gamma = C_1 \frac{\tau}{\lambda Q_n^{1/2}} \tag{1}$$

where τ is the wind stress magnitude, λ is known from air-sea transfer formula and is proportional to the

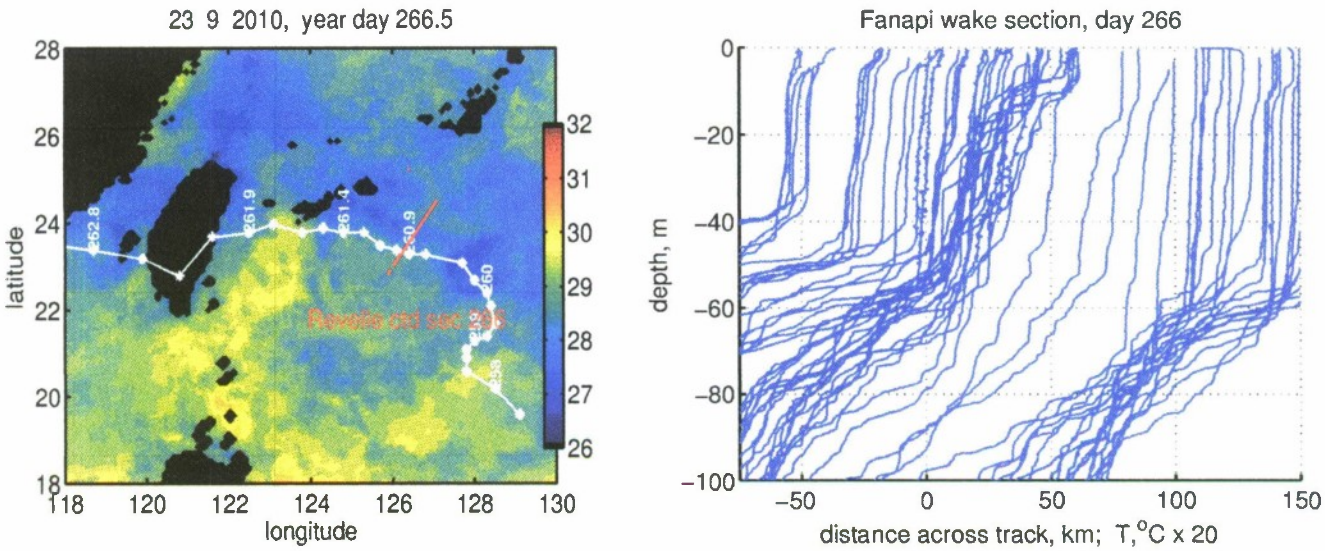

Figure 2: (left) An SST image and thc track of typhoon Fanapi. The R/V Revelle ran a etd seetion across the track and the cool wake on day 266, about six days after the passage of Fanapi. (right) Temperature profilcs across the track. The cool wake occupied about the middle third of this section. Note the thin, warm surface layer above the cool wake. This is direct evidence of the (thin) warm layer hypothesized in H2.

anomalous heat flux assoeiated with the cool SST anomaly, and Q_n is the amplitude of the diurnal maximum of the air-sea heat flux. The leading constant, $C_1 = 2.7 \times 10^{10}$ kg$^{1/2}$ m sec$^{-3/2}$ C^{-1} is a product of known thermodynamic constants and a factor involving the latitude. When plotted in Fig. 1 the stress was represented as $\tau = \rho_a C_d U_{10}^2$ with the drag eoeffieient $C_d = 1.3 \times 10^{-3}$. There are no free constants in this model.

The solution (1) for e-folding timc compares well with the CBLAST examples, giving an e-folding of about five days for Fabian and about 20 days for Frances (Fig. 1). It offers an explanation why the Frances casc was somewhat different post-Frances weather was somewhat disturbed, cloudy and windy partly because of other nearby hurricanes, and the SST recovery was delayed mainly by greater that typical winds.

Work Completed/Results

The ITOP field phase observed several eases of cool wake warming in far greater detail of *in situ* ocean data than has ever been available before. Here we will consider the shipboard meteorology and ctd measurements made from R/V Rcvcllc (Chief Scientist Steven Jayne, WHOI, who is collaborating on this research) during the several week period following the passage of typhoon Fanapi.

Thc shipboard meteorological data allows a high quality estimate of the surfaee heat flux and wind speed required to evaluate thc wakc warming model (the red and green dots of Fig. 1). The predicted

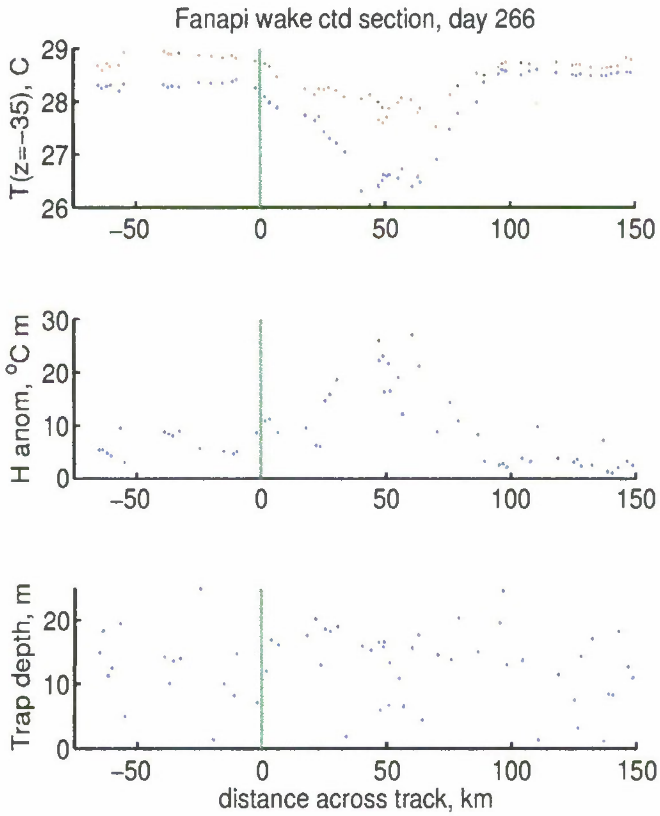

Figure 3: Temperature profile properties from the day 226 ctd section across the track of Fanapi. (upper) The SST and the 35 m temperature (red and blue dots). The cool wake is clearly evident as the cool anomaly centered about 50 km to the right of the track, denoted by the vertical green line. Notice that SST had warmed by almost 1.5 C by the time of this section. (middle) The heat content anomaly with respect to 35 m depth. Notice that the anomaly is very clearly correlated with the cool wake. This is direct confirmation of H1 of the warming model. (lower) The trapping depth, heat content anomaly divide by the surface temperature anomaly. This depth shows quite a lot of variability, about 5 to 15 m over the coolest part of the wake, but is consistent with the expectations of diurnal cycle mean and variability (Fig. 1, right).

e-folding time, roughly one week during the first ten days, is in good accord with the e-folding estimated from satellite imagery and from ocean observations (Mrvaljevic et al, Evolution of the cold wake of Typhoon Fanapi; paper in progress). What was missing from the CBLAST cases was the *in situ* data required to know how deep below the sea surface this warming was actually occurring. In this regard, the ITOP data sets are unmatched.

A ctd section made six days after the passage of Fanapi (Fig. 2) shows that the warming was indeed trapped within the upper 5 - 15 m of the sea surface during the period of rapid warming consistent, consistent with H2. Even more striking, the heat content anomaly is clearly associated with the cool wake (Fig. 3, middle), consistent with H1. Said a little differently, the cool wake warms preferentially because it is relatively cool, and so has reduced heat loss (the sum of sensible, latent and net long wave radiative fluxes). The shallow trapping depth, 5 - 15 m, is consistent with the depth of diurnal cycling (Fig. 1, right).

Impact/Applications

This problem/phenomenon, hurricane wake warming, can be viewed as a test case for warming the ocean surface generally. The key finding here is that the relevant heat flux is made up of two components: a slowly varying mean, here represented by λ, and the diurnally-varying heat flux, here represented by the noon maximum, Q_n. The former determines the trend of surface temperature, and the latter determines the amplitude of the warming by setting the depth over which the mean heat flux is absorbed (i.e., the heat capacity of the ocean surface). The daily average heat flux alone is not sufficient to predict the depth over which the heat flux will be absorbed. This has direct implications for ocean modelling and thermodynamics.

Collaborations

The PI has ongoing collaborations ongoing with Dr. Tom Sanford and Dr. Ren-Chieh Lin, APL/UW, Prof. Shuyi Chen of RSMAS University of Miami and Prof. I-I Lin of National Taiwan University.

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